AMMONIA AND GASEOUS NITROGEN EMISSIONS FROM A COMMERCIAL BEEF CATTLE FEEDYARD ESTIMATED USING THE FLUX-GRADIENT METHOD AND N:P RATIO ANALYSIS

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ABSTRACT. *Micrometeorological methods used to estimate emissions are advantageous because they are noninterfering and can integrate fluxes over large areas. They have not been routinely applied to beef cattle feedyards, where physical complexity and the possibility of disturbed air flow may be problematic. Our objective was to use the flux-gradient method to estimate NH_3 emissions from beef cattle feedyard pens, and compare it to gaseous N loss inferred from analysis of the change in feed and manure N:P ratio. Research was conducted at a commercial feedyard on the High Plains of the Texas Panhandle, during three summer and two winter campaigns, 2002-2004. Profiles of NH_3 concentration, wind speed, and air temperature were measured on 6-m or 10-m towers erected in the feedyard. Ammonia concentration was measured using acid gas washing or chemiluminescence, and NH_3 flux estimated using gradient or finite difference forms of the flux-gradient method. Gaseous N loss was estimated by collecting and analyzing feed and pen surface manure samples for N and P, and using inputs including diet composition, feed fed, head count, and cattle weights. Summer mean daily NH_3 flux ranged from 55 to 93 $\mu g\ m^{-2}\ s^{-1}$, averaging 70 $\mu g\ m^{-2}\ s^{-1}$. Winter NH_3 flux was half that of summer. Ammonia-N emission rate averaged 4650 kg d^{-1} (55% of fed N) during summer and 2140 kg d^{-1} (27% of fed N) during winter. Gaseous N loss averaged 45% of fed N, so that most N was lost as NH_3 during summer, and NH_3 comprised about 60% of gaseous N loss during winter. Ammonia emission factor for this feedyard was 15 kg head^{-1} yr^{-1}, with 50% of fed N lost as ammonia.*

Keywords. *Micrometeorology, flux-gradient, ammonia, flux, emission rate, emission factor, beef cattle, feedyard.*

INTRODUCTION

Micrometeorological methods to determine gaseous emissions to the atmosphere are advantageous because they do not interfere with the processes of emissions and they integrate emissions over larger areas (Harper, 2002; Fowler et al., 2001) Successfully applied to crops (Denmead et al., 1978; Harper and Sharpe, 1995; Rana et al., 1998) and semi-natural vegetation (Bussink et al., 1996; Denmead et al., 1974; Wyers and Erisman, 1998), they have rarely been used to characterize ammonia emissions from beef cattle feedyards (Hutchinson et al., 1982). There are also uncertainties in application of some micrometeorological methods to situations of disturbed flow, such as a feedyard (Wilson et al. 2001), where assumptions of a given method may be violated.

The flux-gradient (FG) method treats turbulent flux as analogous to molecular diffusion, using the expression

$$Q_{FG} = -K_g \frac{\partial \rho_g}{\partial z} \tag{1}$$

where K_g ($m^2\ s^{-1}$) is called the eddy diffusivity (or turbulent transfer coefficient) of the gas of interest,

ρ_g (μg m^{-3}) is the density of the gas, and z (m) is height; the differential expresses the vertical concentration gradient (Harper, 2002). Though eddy diffusivity is analogous to molecular diffusivity, it differs in that it is a characteristic of the flow, not the fluid; it's not a constant, but varies with wind speed and atmospheric stability (Fowler et al., 2001); and because it is related to the size of turbulent eddies, it is proportional to distance from the surface (Thom, 1975). Because K_g is not readily known, it is determined using the momentum balance method to determine the eddy diffusivity for momentum, K_m, which is then related to K_g. This requires profile measurements of gas concentration, wind speed, and air temperature to calculate a FG flux estimate. The FG method assumes that there is horizontal uniformity of air flow, that horizontal concentration gradients are negligible, and that vertical flux is constant with height (Harper, 2002; Thom, 1975).

The N:P ratio of feedyard manure collected from pens is less then the N:P ratio of feed (Mason, 2004), because of differences in retention by the animal, but primarily because N may volatilize from the surface as ammonia or other gases, whereas P does not volatilize. Thus, changes in the N:P ratio from feed to pen manure can be used to estimate an upper limit of ammonia emission from feedyard pens.

Our objective was to use the flux-gradient method to estimate ammonia emissions from a commercial beef cattle feedyard, and compare it to gaseous N emissions inferred from analysis of the change in N:P ratio.

MATERIALS AND METHODS

LOCATION AND SITE CHARACTERISTICS

Research was conducted at a commercial beef cattle feedyard located in the Texas Panhandle. Occupancy of the 88-ha pens ranged from 42,000 head to 49,000 head. Median capacity of feedyards in the region is 30,000 head. Stocking density was about 14 m^2 head^{-1} in summer and about 17 m^2 head^{-1} in winter. Though the terrain is relatively flat, the feedyard surface is complex, with several small buildings, thousands of meters of 1.5-m tall pen fences, electrical poles, manure mounded in centers of pens, and mobile cattle. A retention pond and manure stockpiles are located east of the pens. The semiarid climate of the region is characterized by hot summers and mild winters. Mean annual precipitation is 500 mm, with 75% falling from April through October. Potential evaporation is about 1500 mm, so that summer precipitation often rapidly evaporates. Prevailing winds are southerly to southwesterly, with wind direction almost half the time between 160° and 250°.

Five field campaigns were conducted; during summer 2002, 2003, and 2004, and during winter 2003 and 2004. Conditions during the five campaigns are summarized in Table 1. During each campaign, an instrument tower was installed in a location intended to maximize upwind fetch in the direction of expected prevailing winds. Summer 02, a 6-m tower was centered on the north margin of the pen area; Winter 0,3 a 6-m tower was near the center of the pen area; and in Summer 03, Winter 04 and Summer 04, a 10-m tower was erected near the center of the northeast quadrant of the pen area.

Table 1. Dates of, and meteorological conditions during, five field campaigns conducted at a commercial beef cattle feedyard.

Campaign	Date	Air temperature			Rel. Hum.	Windspeed	Solar Rad.	Precipitation
		Max.	Mean	Min.	Mean	Mean	Mean	Total
			C		%	m s^{-1}	W m^{-2}	mm
Summer '02	19Aug – 24Aug	35	25	19	68	4.7	200	11.7
Summer '03	14Jul – 31Jul	42	28	16	21	2.6	317	0
Summer '04	14Jun – 6Jul	37	23	14	70	5.4	275	69.7
Winter '03	15Jan – 24Jan	24	1.4	-8.8	63	2.4	139	0
Winter '04	29Jan – 9Feb	19	2.1	-8.9	68	3.5	158	tr

ATMOSPHERIC AMMONIA CONCENTRATION

Ammonia concentration was measured during Summer 02, Winter 03 and Summer 03 using acid gas washing. Ammonia was trapped in gas washing bottles by first drawing air through a teflon filter to remove particulates, then bubbling it through an impinger in 80 to 120 ml of 0.1 N H_2SO_4. Air flow rate of each gas washing bottle was measured with a precision, calibrated flow meter (Dry-Cal DC Lite, Bios International, Butler, NJ[1]) at the beginning and end of each sampling period. Nominal air flow rate was 6 L min^{-1}. At the beginning of a sampling period, gas washing bottles with fresh acid were sealed and transported to the tower, exchanged with the bottles there, and sealed bottles with samples were returned to the laboratory, where each sample was diluted to 100 ml with acid, 30 ml was decanted into a sample bottle, and then all samples were refrigerated until analysis. A calibrated flow injection analyzer (QuickChem FIA+ 8000, Lachat Instruments, Milwaukee, WI.) was used to quantify ammonium in the samples, with a minimum detection limit of about 10 µg L^{-1}. This corresponded to atmospheric ammonia concentrations of less than 1 µg m^{-3}. However, experience indicated that the minimum detection limit of atmospheric ammonia was probably closer to 5 - 10 µg m^{-3}. Sampling periods varied from 2 to 4 hours during daytime, and from 2 to 16 hours during nighttime.

During Winter 04 and Summer 04, ammonia concentration was measured continuously using a chemiluminescence analyzer (17C, Thermo Environmental Instruments, Franklin, MA). Ammonia concentration at two different heights (3-m and 6-m) was measured sequentially using a 3-way solenoid that switched gas sampling lines from one height to the other every 10 minutes. Due to the response time of the analyzer, only data from the last 3 minutes out of 10 minutes were averaged.

Profiles of wind speed and air temperature were defined at the same heights as atmospheric ammonia concentration. Cup anemometers (12102M, R.M. Young, Traverse City, MI) measured wind speed and aspirated, fine-wire (25.4 µm diameter) thermocouples (ASPTC, Campbell Scientific, Logan, UT) measured air temperature. Other meteorological measurements included incoming solar radiation (LI200X, Licor Inc., Lincoln, NE), relative humidity and air temperature (HMP45, Vaisala, Helsinki, Finland), wind direction (12005, R.M. Young, Traverse City, MI) and precipitation (TE525, Campbell Scientific, Logan, UT). Outputs from meteorological instruments were automatically recorded to a data logger (CR23X, Campbell Scientific, Logan, UT) that sampled instruments every 5 s and calculated 1-min means.

FLUX-GRADIENT ESTIMATES OF AMMONIA FLUX

When acid gas washing was used, with profile measurements of ammonia concentration at several heights, ammonia flux was estimated from measured profiles of ammonia, wind speed and air temperature using (Thom, 1975)

$$Q_{FG} = \frac{-k^2}{S_c \phi_m^2} \frac{dA}{d[\ln(z-d)]} \frac{du}{d[\ln(z-d)]} \tag{2}$$

where k is Von Karmen's constant (assumed 0.4), A (µg m^{-3}) is ammonia concentration, u is wind speed (m s^{-1}), d (0.45 m) is zero plane displacement height estimated from sonic anemometer measurements of roughness length (z_0=0.09 m), S_c is the Schmidt number ($K_m/K_A = \phi_A/\phi_m = 0.63$ (Flesch et al., 2002; Wilson et al., 2001)), and ϕ_m is an empirical correction for thermal stability calculated as functions of height and the Monin-Obukhov length given in Flesch et al. (2002). When chemiluminescence was used, with ammonia concentration measured at only two heights, ammonia flux was estimated with (Flesch et al., 2002)

[1] Mention of trade or manufacturer names is made for information only and does not imply endorsement, recommendation, or exclusion by USDA-ARS.

$$Q_{FG} = \frac{-k^2}{S_c \phi_m^2} \frac{(z_1 - d)(z_2 - d)}{(z_1 - z_2)^2} \Delta A \Delta u \qquad (3)$$

where ΔA and Δu are finite differences of ammonia concentration and wind speed, respectively, measured at z_1 and z_2 (3-m and 6-m).

Data were screened by wind direction to ensure adequate upwind fetch and to eliminate observations of ammonia concentration that were possibly affected by sources other than feedyard pens, such as the retention pond or manure stockpiles. Mean daily flux was calculated by time-weighted averaging of flux estimates for sampling periods.

GASEOUS NITROGEN LOSSES ESTIMATED USING N:P RATIOS

Diet samples were collected from feed bunks immediately after feeding, before cattle disturbed feed. Samples were routinely obtained from at least five different feed truck loads on at least three days (minimum 15 samples) during each campaign. Samples of dry, loose, unconsolidated manure surface (Woodbury et al., 2001; Mason, 2004) were obtained from six pens each day. Diet and pen surface samples were dried to constant weight in a forced air oven at 60 C to determine dry matter content, then digested in a block digester and total nitrogen and phosphorus determined colorimetrically using a flow injection analyzer.

Feedyard staff provided, for each campaign, total head count, total feed fed, ingredient composition of the diets, and average cattle weights. Average daily weight gain of cattle was estimated using NRC (2000) equations based on the calculated net energy (NE_m = 2.12 mcal kg^{-1} and NE_g = 1.46 mcal kg^{-1}) composition of the diets. Protein retention by cattle was calculated from weight gain using NRC (2000) equations. Nitrogen retention was assumed equal to 16% of protein retention. Phosphorus retention was assumed to be 3.9% of protein gain (NRC, 2000). Total N and P intake were determined by multiplying nutrient concentration by total feed intake. The quantities of N and P excreted (and thus the N:P ratio of freshly excreted manure) were determined by subtracting the nutrient retained by animals from the total nutrient intake. Total gaseous N volatilized from feedyard pens was estimated as follows. The difference in the N:P ratio of the excreted manure (6:1, for example) and pen surface manure (2:1, for example) represented the quantity of N that was lost for each unit of P that was excreted (4 in this example). Dividing the difference by the N:P ratio of the diet provided an estimate of the percentage of feed N volatilized from the pen surface.

RESULTS AND DISCUSSION

All ammonia concentration profiles measured above feedyard pens were examined for adherence to a logarithmic profile. In most profiles, measurements at 1-m and 10-m heights deviated from a log-linear fit. At z=1 m, concentration was underestimated because towers were located at a distance from the nearest pen with cattle that varied with wind direction, and the intervening area was not an active ammonia source. At z=10 m, concentration was underestimated because the upwind footprint that affected the concentration extended beyond the feedyard. Footprint analysis using the methods of Schuepp et al. (1990) indicated that most ammonia concentration measurements at z=8 m lacked sufficient fetch and were most likely underestimated. Exclusion of these data yielded excellent log-linear fits of profile data. Therefore, all flux calculations used NH_3, wind and temperature measurements between 2 and 6 m.

Ammonia concentration followed a typical diel course (Fig. 1). Concentration increased from early morning and reached a daytime maximum near midday, then decreased into the early evening. Maximum concentrations, sometimes exceeding 3000 μg m^{-3}, were measured at night during strongly stable conditions.

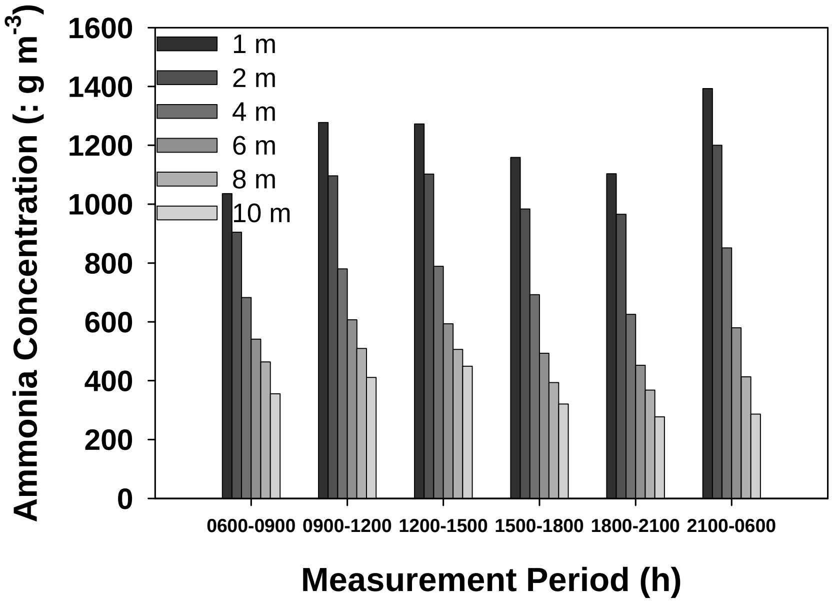

Figure 1. Composite atmospheric ammonia profiles. Each measurement period is the mean of ammonia concentration during that time period for nine days from Summer 03.

Mean daily NH_3 flux density was highly variable from campaign to campaign (Table 2). Summer flux ranged from 55 to 93 μg m^{-2} s^{-1}, averaging 70 μg m^{-2} s^{-1}. Greatest variability (CV=51%) was observed during Summer 04 and was related to frequent precipitation during the campaign. Flux was suppressed following precipitation and increased as feedyard pens dried. In contrast, CV during Winter 03 and Summer 03, when there was no precipitation, were 11% and 16%, respectively. Greatest flux was observed during Summer 03, when environmental conditions were hot and dry (Table 1). Maximum daily flux was 110 μg m^{-2} s^{-1} on 14Jul2003, and the greatest 3-hr flux, 199 μg m^{-2} s^{-1}, occurred during early afternoon of that day. Winter flux density was half that of summer, averaging 34 μg m^{-2} s^{-1}. Hutchinson et al. (1982) reported mean ammonia flux of 47 μg m^{-2} s^{-1} from 5 daytime periods during spring and summer in a northern High Plains feedyard. They also observed suppressed flux when the surface was wet and enhanced flux when it was hot and the surface was drying. Ammonia-N loss in this study averaged 4650 kg d^{-1} during summer and 2140 kg d^{-1} during winter. Assuming that the average of summer and winter NH_3-N emission rates (3400 kg d^{-1}) was representative of the mean daily emission rate throughout the year, and that the annual production of the feedyard was 100,465 head (2.25 turnovers yr^{-1}), gives an emission factor of 15.0 kg NH_3 $head^{-1}$ yr^{-1}. In comparison, the ammonia emission factor assigned to beef cattle in drylots by USEPA (2004) was 11.4 kg NH_3 $head^{-1}$ yr^{-1}.

Table 2. Ammonia emissions from feedyard pens. Mean daily flux is averaged from time-weighted means for the quality days in a campaign. Ammonia-N emission rate is calculated from flux and area of feedyard pens. Coefficient of variation (CV) is for the mean of mean daily flux.

Campaign	Date	No. of quality days	Mean daily NH_3 flux	Mean daily NH_3-N emission rate	CV
			μg m^{-2} s^{-1}	kg d^{-1}	%
Summer 02	19Aug-23Aug	4	61	4650	22
Summer 03	14Jul-1Aug	9	93	5860	16
Summer 04	14Jun-6Jul	9	55	3450	51
Winter 03	15Jan-24Jan	7	23	1470	11
Winter 04	26Jan-6Feb	5	44	2800	27

On average, the N:P ratio changed from 5.49 in the feed to 2.99 in the manure pack during summer, and from 5.96 to 3.28 during winter (Table 3). Gaseous N could include forms such as NH_3, NO_3, or N_2, and so represented a potential upper bound for NH_3-N loss. Gaseous N lost averaged 45% of fed N in summer and 44% of fed N in winter. Ammonia-N loss averaged 55% of fed N during summer and 27% of fed N during winter. These results suggest that most N is lost as NH_3 during the summer, and that NH_3 comprises about 60% of the gaseous N loss during the winter. Erikson and Klopfenstein (2001) used a nitrogen balance method and estimated that in Nebraska 60-70% of fed N was lost as gaseous N during summer, and 40% during winter-spring. In an independent study coincident with this study at the same feedyard, Harper et al. (2004) used open path lasers to measure ammonia concentration and a backward Lagrangian stochastic (BLS) model to estimate flux. They found that summertime emissions were 53% of fed N and wintertime emissions were 29% of fed N.

Table 3. Fed dry matter and N:P, head count, weight gain, manure pack N:P; gaseous N lost from feedyard pens based on change in N:P from feed to manure pack, and NH_3-N loss as estimated using flux-gradient method, both expressed as percentage of fed N.

Campaign	Fed Dry matter	No. head	Feed N:P	Shrunk weight gain	Manure pack N:P	N lost as fraction of fed N, N:P method	NH_3-N lost as fraction of fed N, FG method
	kg hd^{-1} d^{-1}			kg d^{-1}		%	%
Summer 02	7.56	42,804	5.64	1.26	3.30	41	67
Summer 03	6.99	48,463	5.26	1.12	3.09	41	65
Summer 04	8.28	49,109	5.57	1.13	2.59	54	32
Winter 03	7.62	43,157	7.00	1.28	3.65	48	21
Winter 04	7.17	41,863	4.93	1.16	2.91	41	33

Formulation of the diet was changed in April 2003 and crude protein content increased from 13.5% to 14.5%. Optimal crude protein in beef cattle diets is about 13% (Gleghorn et al., 2004), so that the new diet provided excess N. Consequent with the increase in fed nitrogen was an increase in NH_3-N emissions. From Summer 02 (old diet) to Summer 03 (new diet), fed nitrogen increased 2070 kg d^{-1} and emission rate increased by 1210 kg NH_3-N d^{-1}. From Winter 03 (old diet) to Winter 04 (new diet) fed nitrogen increased 1510 kg d^{-1} and emissions increased by 1330 kg NH_3-N d^{-1}. Cole et al. (2003) showed in a closed chamber experiment that increasing dietary crude protein from 13% to 14.5% did not increase ammonia emission from manure, because urinary excretion from steers fed the two diets did not differ. Increasing dietary crude protein from 11.5% to 13%, however, did increase ammonia emission from manure by 79% in a laboratory chamber experiment and by 42% in a field experiment conducted over all seasons (Todd and Cole, unpub. data). It is inconclusive, in the more complex conditions of a commercial feedyard, whether excess dietary N contributed to the increase in NH_3 emissions.

Considerable uncertainty exists in the FG method when used in disturbed flow conditions like a feedyard (Wilson et al., 2001). In a comparison of FG flux estimates of pond emissions to those of a verified local advection model and other flux estimate methods, Wilson et al. (2001) found that the FG method consistently underestimated flux, with deviations greatest during stable conditions and at greater measurement heights. Flux estimates using the FG method are also sensitive to values chosen for zero plane displacement height and the Schmidt number. For example, when d increases from $5z_0$ to $7z_0$, flux decreases by about 12%. Flesch et al. (2002) estimated uncertainty in S_c at 20%. For equations used in this study, when S_c increases from 0.63 to 0.75, flux decreases by about 16%. Ammonia-N lost as a fraction of fed N exceeded the upper bound of gaseous N loss (estimated using the change in N:P) by 60% during Summer 02 and Summer 03, suggesting overestimation. However, on an annual basis (NH_3-N and gaseous N loss as mean of summer and winter losses), NH_3-N loss was

91% of gaseous N loss. Encouraging for use of the FG method in a feedyard situation is the close agreement between the method and the independent laser/BLS method of Harper et al. (2004).

CONCLUSION

The micrometeorological flux-gradient method can be used to reasonably estimate ammonia fluxes from a commercial beef cattle feedyard. Measurements of ammonia concentration, wind speed and temperature adhered to log-linear profiles when measurements at heights of 1, 8, and 10 m were excluded from analysis because of underestimated ammonia concentration. The flux-gradient method is sensitive to zero plane displacement height and Schmidt number, and their estimation contributes to uncertainty in flux estimates.

Ammonia emissions during summer were greatest during hot, dry weather. Precipitation suppressed ammonia emissions, which subsequently increased as pens dried. Winter emissions of ammonia were half those during summer. Analysis of the change in N:P ratio from feed to manure indicated that 45% of fed nitrogen was lost as some form of gaseous N. Flux-gradient estimates of ammonia-N loss averaged 55% of fed N during summer and 25% of fed N during winter, suggesting that most N was lost as ammonia during summer, and that ammonia was about 60% of gaseous N lost during winter. When the average of mean summer and mean winter ammonia emission rates was assumed representative of the annual emission rate, the ammonia emission factor for this typical, southern High Plains feedyard was 15 kg head^{-1} yr^{-1}, with 50% of fed N lost as ammonia.

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